Forming Intermediate-Mass Black Holes in Dense Clusters Through Collisional Run-away

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Routes to form (I)MBHs

Cluster of MS stars with IMF

Core-collapse through mass-segregation

Is there "not too hard" binaries?

Collapse stalls

Massive stars evolve before core collapse
Strong mass loss (if metallicity high enough)

Gas lost from cluster?

Disruptive collisions

VMS grows into a SMS?

Core-collapse through mass-segregation

Run-away formation of VMS

Massive gas cloud + stars

Efficient ejection?

Remnants merge by GW emission

IMBH has formed!

VMS turn into an IMBH?

Growth to MBH?

Delivery to galactic centre?
Run-away collisions to form (I)MBHs?

(Rasio, Freitag & Gürkan, 2003; Gürkan, F & R, 2004; Freitag, G & R, in prep.)

● **How it should work**

1. If collisions (mergers) faster than stell. evol.: Run-away formation of a very massive star (VMS, $M_*>100\, M_\odot$). Mass-segr. $\Rightarrow T_{\text{coll}}\ \\downarrow\downarrow$

2. If low metallicity, VMS leaves an IMBH as remnant.

● **It worked...** in previous numerical simulations

Quinlan & Shapiro 90: Fokker-Planck models of proto-galactic nuclei. **But:** unphysical IMF (single-mass) & treatment of collisions

Portegies Zwart & McMillan 02; Portegies Zwart et al. 04: $N$-body models of populous young clusters. Binaries may foster collisions.

● **But can it really work in proto-galactic nuclei, with $\sigma_v \approx \text{few } 100\, \text{km s}^{-1}$?**

  * Binaries play little role. Single–single collisions occur as $\rho_c \nearrow\nearrow$

  * Mergers ($\delta M_*>0$) vs. disruptive collisions ($\delta M_*<0$)??
Monte Carlo stellar dynamics code


● Goal: simulate $10^{6−9} \times$ cluster over $10^{6−10}$ yrs

Chosen method: Hénon’s MC scheme

Direct $N$-body: $T_{\text{CPU}} \propto N^{2−3}$

MC code: $T_{\text{CPU}} \propto N \ln(N)$

● Strengths and limitations from 3 assumptions:

**Spherical sym.**

◆ Cluster = set of spherical shells
  
  Shell = symmetrised contribution of 1–many $\times$ with same properties

◆ Time step: fraction of $T_{\text{relax}}(R)$ and/or $T_{\text{coll}}(R)$
  
  Avoids explicit orbital integration

**Dyn. equilibrium**

**Diffusive relaxation**

● Allows rich physics:

◆ Cluster (+central BH) self-gravity; $\vec{V}$–anisotropy; Any $M_*–$spectrum

◆ 2-body relaxation; Stellar collisions (from SPH); Stellar evolution

◆ Tidal disruptions; Horizon-crossings; GW-captures (“loss-cone”)
Phase I: Mass-segregation induced core collapse

\[ T = 0 \]
\[ R_{10}\% = 0.20 \text{ pc} \]

\[ T = 7.22 \times 10^{-3} \quad T_{\text{rh}} = 2.03 \times 10^{6} \text{ yrs} \]
\[ R_{10\%} = 0.24 \text{ pc} \]

Stellar radii magnified $1.6 \times 10^4$ times

Stellar radii magnified $2.0 \times 10^4$ times
Mass-segregation induced core collapse

Following the central densities and velocity dispersions evolution with “gaseous model” (15 mass components)...

The velocity dispersion of the most massive stars do not increase until very late collapse.
How fast can core-collapse be?

Plummer models with various mass functions.
How fast can core-collapse be?

King models with various concentrations.

With a broad mass spectrum, \( T_{cc} \simeq 0.1 - 0.2 T_{rc}(0) \)!
How fast need core-collapse be?

Goal: bring massive stars to the centre before they evolve off the MS.

Sources: Bressan et al. 93, Hurley et al. 00, Belczynski et al. 02
Phase II: Let the massive stars collide!

- **Collision probability** between neighboring particles:
  \[ P^{(12)}_{\text{coll}} = n V_{\text{rel}} S^{(12)}_{\text{coll}} \delta t \quad \text{with} \quad S^{(12)}_{\text{coll}} = \pi b_{\text{max}}^2 = \pi (R_1 + R_2)^2 \left[ 1 + \left( V^{(12)}_{\ast} / V_{\text{rel}} \right)^2 \right] \]
  \[ V^{(12)}_{\ast} = \sqrt{2G(M_1 + M_2) / (R_1 + R_2)} \]

- **Monte Carlo sampling** of collision initial conditions:
  - particles properties → \( V_{\text{rel}}, M_1, M_2 \)
  - impact parameter according to \( \frac{dP}{db} \propto \frac{b}{b_{\text{max}}} \)

- **Any prescription** can be used for the outcome of collisions
  - **Interpolation between the results of SPH simulations** by Delaunay triangulation in 4D \((M_1, M_2, V_{\text{rel}}, b)\)-space

- **BEWARE:**
  - Extrapolation for \( M_{\ast} > 75 M_{\odot} \). ∃ interpolation artifacts!
Collisions in the MC runs: Collisional “rejuvenation”

- Stellar evolution of collisional products: unsolved problem
- We assume:
  - Stars contract back to thermal equilibrium instantaneously
  - They always have MS structure with univocal $M - R$ relation
  - “Minimal” rejuvenation during collisions: the He cores merge together, the H envelopes combine to form new envelope, only H is lost during collisions.
  - Effective age set by mass of core He: $M_{c}^{He}(t) = M_{c}^{He}\big|_{TMS} \cdot \frac{t}{t_{MS}}$
Missing the run-away phase...

Note the second collapse, caused by stellar BHs.

Their density reaches $3 \times 10^{11} \text{pc}^{-3}$ at the end!
Run-away formation of a very massive star
Run-away formation of a very massive star

Merging tree for the formation of a 5000 $M_\odot$ star.

Most mass comes from stars of $\sim 100 M_\odot$
The fast core-collapse domain

Condition for Run-away collisions: \( T_{cc} < 3 \text{ Myr} \iff T_{rc} < 20 \text{ Myr} \)
Open questions...

- **Stellar dynamics**
  - Role of binaries
  - “Loss-cone” effects for collision with the VMS
  - What is the minimum number of stars in the core for the run-away to work?

- **Hydrodynamics**
  - Collisions featuring VMS (is there a “transparency problem”?)

- **Stellar evolution**
  - Role of pre-MS phase
  - Stability and evolution of VMS subject to constant “accretion” of other stars
  - End product of VMS evolution: an IMBH?